

NEUTRINO CROSS SECTIONS

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The next generation of neutrino oscillation experiments aims to answer many interesting questions, such as whether there is CP violation in the neutrino sector and whether sterile neutrinos exist. These experiments will require high precision cross-section measurements of various neutrino and anti-neutrino interaction channels. We review results and prospects for such measurements from the MiniBooNE, T2K, MINER ν A and ArgoNeuT collaborations.

1 Introduction

The discovery of neutrino oscillations and non-zero neutrino mass has led to an interesting new set of neutrino-related questions. For instance, while the neutrino mixing matrix is increasingly well-measured, the origin of the dissimilarity between this matrix and the quark mixing matrix is unknown. It is also unknown whether there is CP violation in the neutrino sector, or whether there exist additional neutrinos (called “sterile neutrinos”) beyond those that have already been observed. In the coming decades, neutrino physicists will attempt to answer some of these questions through long- and short-baseline oscillation experiments.

Generally speaking, neutrino oscillation experiments work by producing a beam of neutrinos and letting it propagate over a distance of hundreds of meters (in the case of short-baseline experiments) to thousands of kilometers (in the case of long-baseline experiments) before being detected in a neutrino detector. Oscillations are then inferred by comparing the observed neutrino energy spectrum with predicted spectra given various oscillation hypotheses. The predicted spectra require knowledge of neutrino interaction rates in the detector. Oscillation experiments therefore require high precision measurements of neutrino interaction cross section in various materials. This is particularly true of the next generation of oscillation experiments, which aim to measure much smaller effects (such as CP violation) than their predecessors.

The range of neutrino energies of interest to oscillation experiments varies from roughly 200 MeV to 10 GeV. Several dedicated neutrino cross-section experiments, such as MINER ν A and ArgoNeuT, have been developed to study neutrinos in this energy range. Additionally, oscillation detectors, such as MiniBooNE and the T2K near detector (ND280), can double as cross-section experiments. Below, we briefly review the types of neutrino interactions that occur in this energy range, and then review results from these four experiments. While many other experiments have measured neutrino interaction cross sections in recent years, we restrict ourselves to the experiments mentioned above due to time and length restrictions.

Because all of the detectors discussed here sit in muon neutrino or muon anti-neutrino beams, all of the reviewed cross-section results are of muon neutrino or muon anti-neutrino interactions, although we note that some experiments also plan to make measurements of the small electron-neutrino component of their beam. Additionally, we review only neutrino interactions with nuclei. While neutrino interactions with electrons do occur, and will be probed by experiments such as MINER ν A, an understanding of neutrino-nucleus interactions is most crucial to oscillation experiments and is thus the focus of this summary.

2 Overview of Neutrino Interactions

When a neutrino interacts with a nucleus within a particle detector, it can exchange either a charged W or a neutral Z boson with the nucleus; these interactions are called “charged-current” or “neutral-current”, respectively. Each of these interactions and their relevance to oscillation experiments is described below.

2.1 Neutral-Current Interactions

Neutral current interactions are characterized by the presence of a neutrino in both the initial and final states. Because neutrinos are invisible to particle detectors, it is difficult to reconstruct the energy of the incoming neutrino in neutral current interactions, and they are generally not used as signal processes in oscillation experiments. Understanding their cross sections is still important, as neutral current interactions can be backgrounds to oscillation signals. In particular, the channel often referred to as “neutral current π^0 production” ($\nu N \rightarrow \nu \pi^0 X$) often appears in a detector as a single π^0 , which can fake a signal electron in a ν_e appearance measurement.

2.2 Charged-Current Interactions

Charged-current neutrino-nucleus interactions are characterized by the presence of a charged lepton (matching the flavor of the initial state neutrino) in the final state. The absence of a neutrino in the final state makes energy reconstruction of these interactions considerably simpler than for neutral-current interactions, and charged-current interactions are often used as signal channels in oscillation measurements. Of particular interest is the channel known as “charged-current quasi-elastic (CCQE)”:

$$\nu_\mu n \rightarrow \mu p \tag{1}$$

$$\bar{\nu}_\mu p \rightarrow \bar{\mu} n. \tag{2}$$

If one assumes that the initial state nucleon is at rest, the kinematics of this interaction can be completely reconstructed using muon kinematics only.

Figure 1 summarizes our current knowledge of charged-current neutrino scattering cross sections. It shows that quasi-elastic scattering is the dominate charged-current cross section below 1 GeV, but at higher energies other processes such as resonant pion production and deep inelastic scattering become dominant. The resonant pion channel, particularly in cases where the pion has too little momentum to

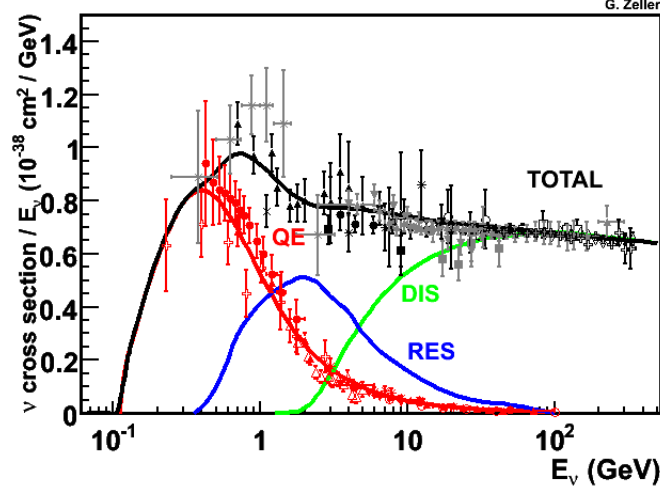


Figure 1. Summary of the current knowledge of ν_μ charged-current cross sections. Plot courtesy of G. Zeller [1].

be seen in a detector or is absorbed in the target nucleus, is a common background to quasi-elastic scattering signals.

2.3 Nuclear Effects

Interpretation of both oscillation and cross-section measurements is complicated by the fact that modern neutrino detectors are usually made of heavy nuclei. Neutrino interactions with nucleons bound within a nucleus differ from those with free nucleons in a number of ways.

- The interaction cross section for bound nucleons is reduced by effects such as Pauli blocking, particularly in the kinematic region where the momentum transferred from the neutrino to the nucleon is low.
- The initial-state nucleon has a non-zero Fermi-momentum, which effectively smears kinematic reconstruction that typically assumes a nucleon at rest.
- Final state particles can undergo interactions as they traverse the nucleus. These interactions can result in significantly different final-states than were produced by the primary interaction.
- Neutrinos can interact with multi-nucleon bound states within the nucleus. Whether such interactions contribute significantly to the total interaction cross section is currently unclear. If they do, this could have significant implications for oscillation experiments, as they may be difficult to distinguish from single-nucleon final-states in many detectors.

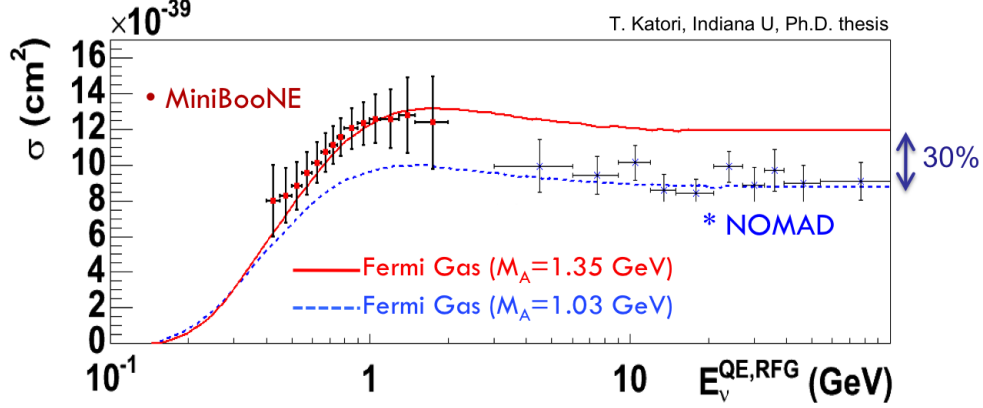


Figure 2. MiniBooNE ν_μ charged-current quasi-elastic cross-section measurements [2,4] as a function of neutrino energy, compared with results from the NOMAD experiment [3]. Plot courtesy of T. Katori.

All of these effects may vary depending on the type of nucleus involved in the interaction. Untangling these various effects and understanding how they vary with different nuclei is a primary focus of neutrino cross-section experiments.

3 MiniBooNE

Although most famous for short-baseline oscillation measurements, the MiniBooNE collaboration has also been a prolific source of cross-section measurements. Located in the Booster neutrino beam at Fermilab, the MiniBooNE detector is a 12.2 diameter sphere of mineral oil surrounded by 1280 photo-multiplier tubes, which detect both Cerenkov and scintillation light produced by neutrino interactions within the mineral oil. The detector sees an average neutrino energy of approximately 700 MeV.

One of MiniBooNE's first cross-section measurement was of the ν_μ charged-current quasi-elastic channel [2], shown in figure 2. One parameter measured by MiniBooNE is " M_A " – the mass term in the axial form factor. While many previous experiments have measured M_A to be near unity [12], the MiniBooNE data prefer a higher value of $M_A = 1.35 \pm 0.17$ GeV/c². The origin of this discrepancy is currently unclear, but one hypothesis is that the MiniBooNE measurement includes quasi-elastic-like interactions that involve neutrino interactions with multi-nucleon states. This topic has become a rich field of theoretical speculation (see for example [13,14,15]), and investigating the multi-nucleon contribution to the quasi-elastic cross section is likely to be a major focus of future quasi-elastic measurements.

Following this very interesting quasi-elastic result, MiniBooNE has gone on to produce eight neutrino cross-section papers [2,5,6,7,8,9,10,11], measuring most of the interactions present in their ν_μ beam. The collaboration is currently working on similar measurements using their $\bar{\nu}_\mu$ -enhanced beam and on reassessing all of their measurements in light of the new possibility of neutrino interactions with

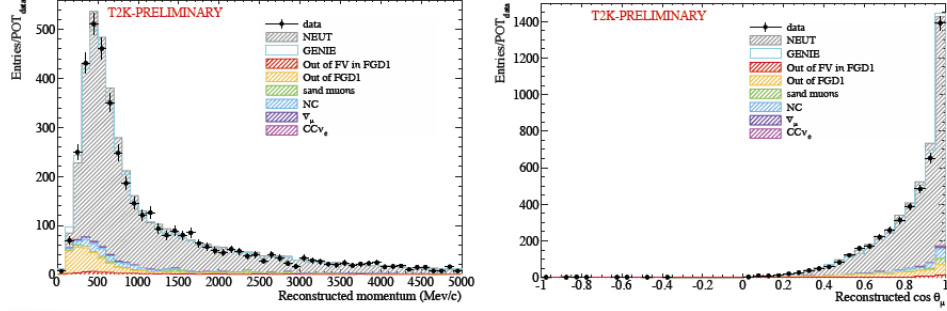


Figure 3. Muon momentum and angular distributions in T2K's charged-current quasi-elastic sample.

multi-nucleon states.

4 T2K

The off-axis T2K near detector [16], known as ND280, serves as the near companion to the Super-K detector for T2K's long baseline studies. It is intended to measure neutrino interaction cross sections and other inputs needed for oscillation results. It is composed of several detectors, including an upstream π^0 detector made of scintillator and water, fine grained detectors composed of 1 cm square bars of scintillator, and time projection chambers. ND280 is somewhat unusual among neutrino cross-section detectors in that it includes a magnet, creating a 0.2 T magnetic field in the inner detectors. The detector sits about 2.5 degrees off axis in a neutrino beam generated at the J-PARC accelerator facility and experiences a beam with a mean neutrino energy of around 700 MeV.

T2K's first cross-section measurement is an inclusive measurement of all charged-current channels [17]. The muon momentum and angular distributions of this sample are shown in Figure 5. They find a total flux-averaged cross section of $(6.93 \pm 0.13 \pm 0.085) \times 10^{-39} \text{ cm}^2/\text{nucleon}$, which is consistent with generator predictions that have been tuned with prior data. They have further divided this sample into quasi-elastic and non-quasi-elastic enriched samples [18], and have fit these samples to extract cross-section parameters that are used in their oscillation measurements. The collaboration will begin producing an array of complete cross-section measurements soon, and may also make cross-section measurements using

5 MINERνA

The MINERνA experiment is a dedicated neutrino cross section experiment located in the NuMI beamline at Fermilab. It contains a large volume of plastic scintillator interspersed with various inactive materials. The upstream portion of the detector includes modules of inactive carbon, iron, lead, water and helium, which will be used

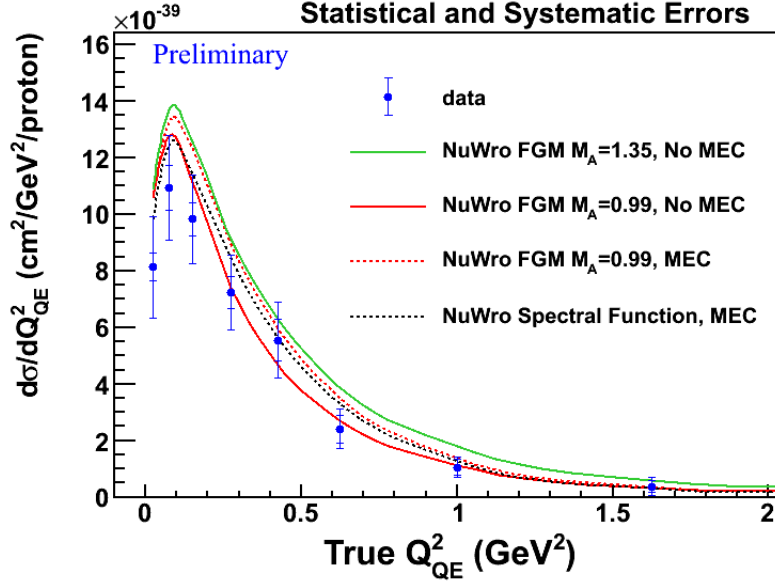


Figure 4. $\bar{\nu}_\mu$ differential cross sections measured in MINER ν A, compared with various models. The models labeled “MEC” include interactions on multi-nucleon [15]. bound states.

to compare neutrino interaction cross sections on different nuclei. The detector sits just upstream of the MINOS near detector, which functions as MINER ν A’s muon spectrometer.

The MINER ν A collaboration has recently presented its first cross section measurement, a flux-integrated $\bar{\nu}_\mu$ quasi-elastic differential cross section with respect to Q^2 (where Q is the 4-momentum transferred from the initial-state neutrino to the final-state nucleon), shown in Figure 4. This differential cross section has also been compared with various models, including those that include a multi-nucleon enhancement to the quasi-elastic cross section. While the data do not yet have sufficient statistical power to rule out any model, the collaboration has more than a factor of three times more data on tape as well as plans to significantly improve systematic uncertainties, making it likely that MINER ν A will have a more definitive statement on the presence of significant multi-nucleon contributions in the near future.

The MINER ν A collaboration has also recently presented preliminary results in a variety of other channels, including several pion channels and ν_μ quasi-elastic interactions in both scintillator and the nuclear targets. The experiment expects to publish its first papers using its initial low energy run in the next year, and will also begin a medium energy run using the NO ν A configuration of the NuMI beam in 2013.

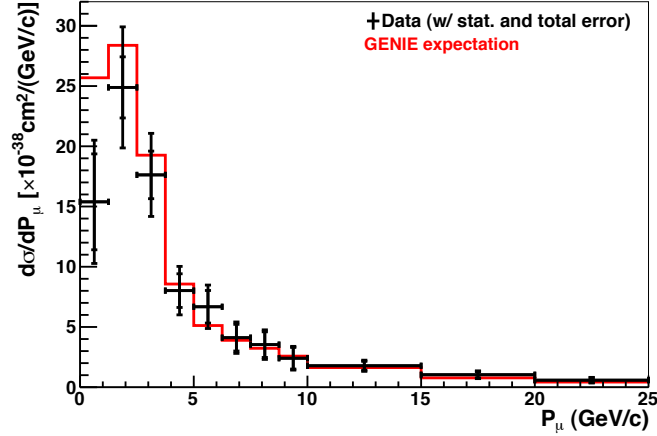


Figure 5. Muon momentum spectrum in ArgoNeuT's ν_μ charged-current inclusive sample.

6 ArgoNeuT

The ArgoNeuT detector is a 170 liter liquid Argon TPC that sat between MINER ν A and the MINOS near detector during several months of 2009 and 2010. As the first liquid Argon detector to reside in a low-energy neutrino beam, ArgoNeuT is an important step in the development of kiloton-scale liquid Argon detectors. Liquid Argon TPCs offer resolution comparable to bubble chambers, which gives it unprecedented ability to visualize interactions. Of particular interest is ArgoNeuT's ability to reconstruct activity near the interaction vertex, which is a sensitive probe of nuclear effects. ArgoNeuT's first cross section measurement is of the charged-current inclusive cross section, where they find $\sigma/E_\nu = (7.3 \pm 1.2) \times 10^{-39} \text{ cm}^2/\text{GeV}/\text{nucleon}$ at $\langle E_\nu \rangle = 4.3 \text{ GeV}$, which is consistent with Monte Carlo predictions [19]. The collaboration is now working towards measurement of exclusive channels, including charged-current quasi-elastic.

7 Conclusion

The field of neutrino cross section measurements is both rich and important. The next generation of neutrino oscillation experiments will require a wide array of well-measured neutrino interaction cross sections. Because neutrinos interact with nucleons bound within the nuclei of neutrino detectors, making such measurements also gives us a unique glimpse at nuclear structure. Several experiments which have measured cross sections, such as MiniBooNE and ArgoNeuT, have completed data-taking and are currently making their final measurements. Others, such as MINER ν A and T2K's ND280, are in the midst of their data runs and have begun producing preliminary results that show much promise for the future. In the next few years, new experiments such as MicroBooNE, ICARUS and the NO ν A near detector will come online, ensuring that the field of neutrino cross section

measurements will be active for many years to come.

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